Summary of USGS Simulation Capabilities and Tools Relevant to the Understanding of Salinity in the Central Valley and to the Development of Salinity Management Plans

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This document provides a summary for the Salinity Policy Group of various capabilities and tools developed by the US Geological Survey (USGS) that have relevance to the mission of the Group. These capabilities and tools fall into three categories: accounting for the influence of geology on the ground-water flow system; simulation tools; and recently-developed multi-scale models in the Central Valley. Included in discussions of these categories are examples highlighting the relevance to understanding the salinity distribution and to exploring salinity management options.

Accounting for the influence of geology on the ground-water flow system

It is well understood that sedimentary aquifer systems are highly heterogeneous, or have a non-uniform distribution of sediments typically ranging in texture from clay to gravel. Nonetheless, a typical ground-water flow model is constructed in layer-cake fashion where layers are defined by similar sediment types (ex. clays, sands, gravels, etc), and hydraulic properties are often uniform within layers, or varied among a few delineated zones (Fig. 1).

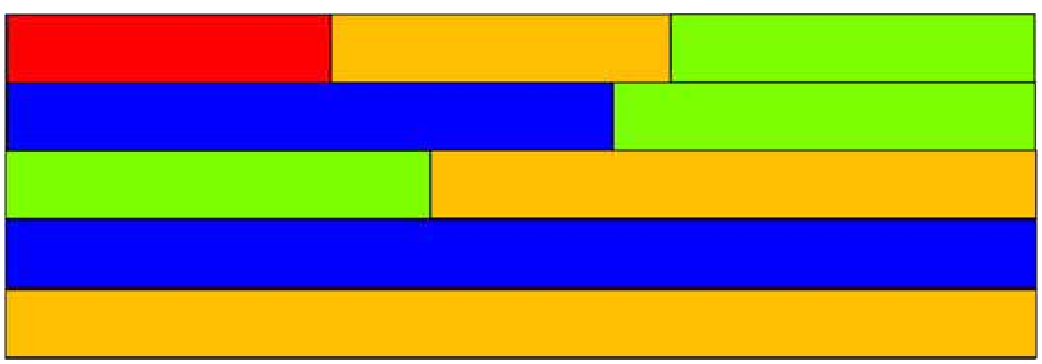

Fig. 1. *Typical "layer-cake" model construction*

There are several drawbacks to this approach, chief among them the dependence of simulated flow and solute transport on the construction of the "layer cake" flow system. Different layer properties and configurations can match measured water levels equally well, but simulated flow paths and associated velocities may vary widely; actual flow paths may differ greatly from those derived from this simplistic layering. Additionally, the simulated transport of solutes in a "layer-cake" model is highly dependent on the assigned values for dispersion, which depend on the degree of heterogeneity, which has been minimized by the lithologic averaging used to construct the layers.

The USGS has addressed these drawbacks by explicitly incorporating the heterogeneity of hydraulic properties on the basis of the distribution of sedimentary deposits and/or textures. This has been done in a variety of ways, but typically involves the use of thousands of relatively high-quality drillers' logs and geostatistical methods for estimating the texture distribution between these logs. The result is a more realistic-looking representation of the aquifer system (Fig. 2).

Models used for developing an understanding of the long-term evolution of salinity in the Central Valley, and ultimately for developing salinity management plans, will need to accurately account for the influence of geology. Directions and rates of ground-water flow and associated solute transport are highly dependent on the three-dimensional distribution of sedimentary deposits. The general method described here was used in developing all of the models discussed in the final section of this document.

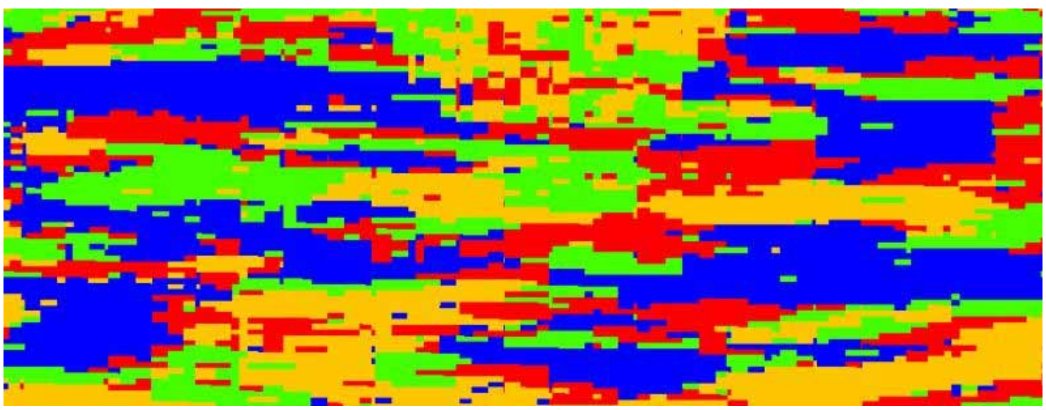

Fig. 2. *More realistic model construction*

Such representations of the aquifer system result in far more realistic simulation of ground-water flow. Simulation of solute transport is much improved and is far less dependent on the assigned values for dispersion, which instead is largely accounted for by explicitly incorporating heterogeneity.

Simulation tools

MODFLOW is the primary model of the USGS, is the most-used ground-water model world wide, and is rigorously tested and verified. It has also been the focus of recent efforts to update and improve USGS simulation capabilities. Among these improvements are several aspects relevant to the Salinity Policy Group:

The FARM Process

This is an advanced tool for simulating the movement and consumption of water related to a wide variety of land use such as irrigated agriculture, natural and riparian vegetation and urban areas. This MODFLOW process can also optionally be used to simulate constraints of water delivery such as surface- water rights as well as other mechanisms to better represent reality and/or to explore management alternatives.

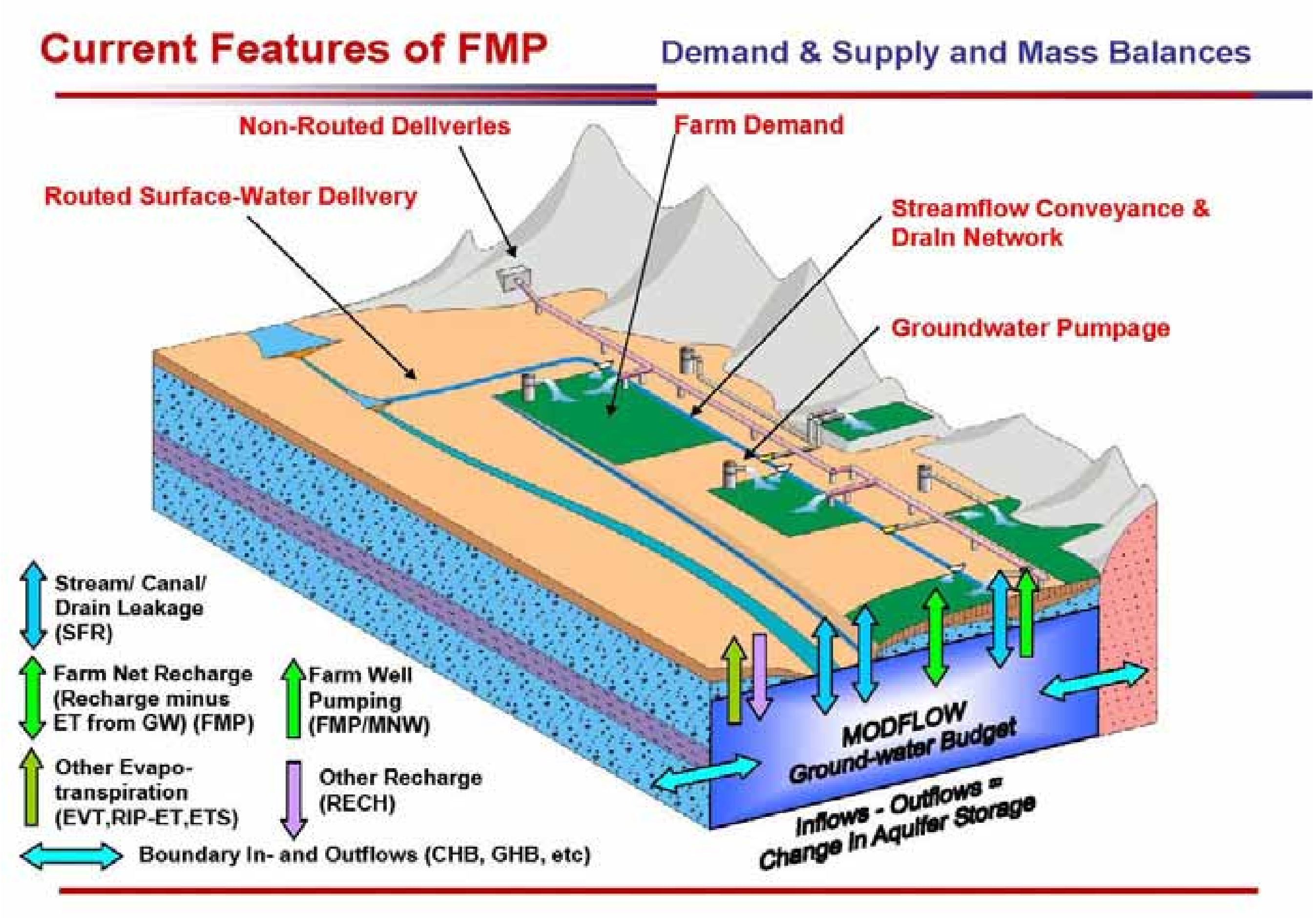

Fig. 3. Key features of the FARM Process in MODFLOW

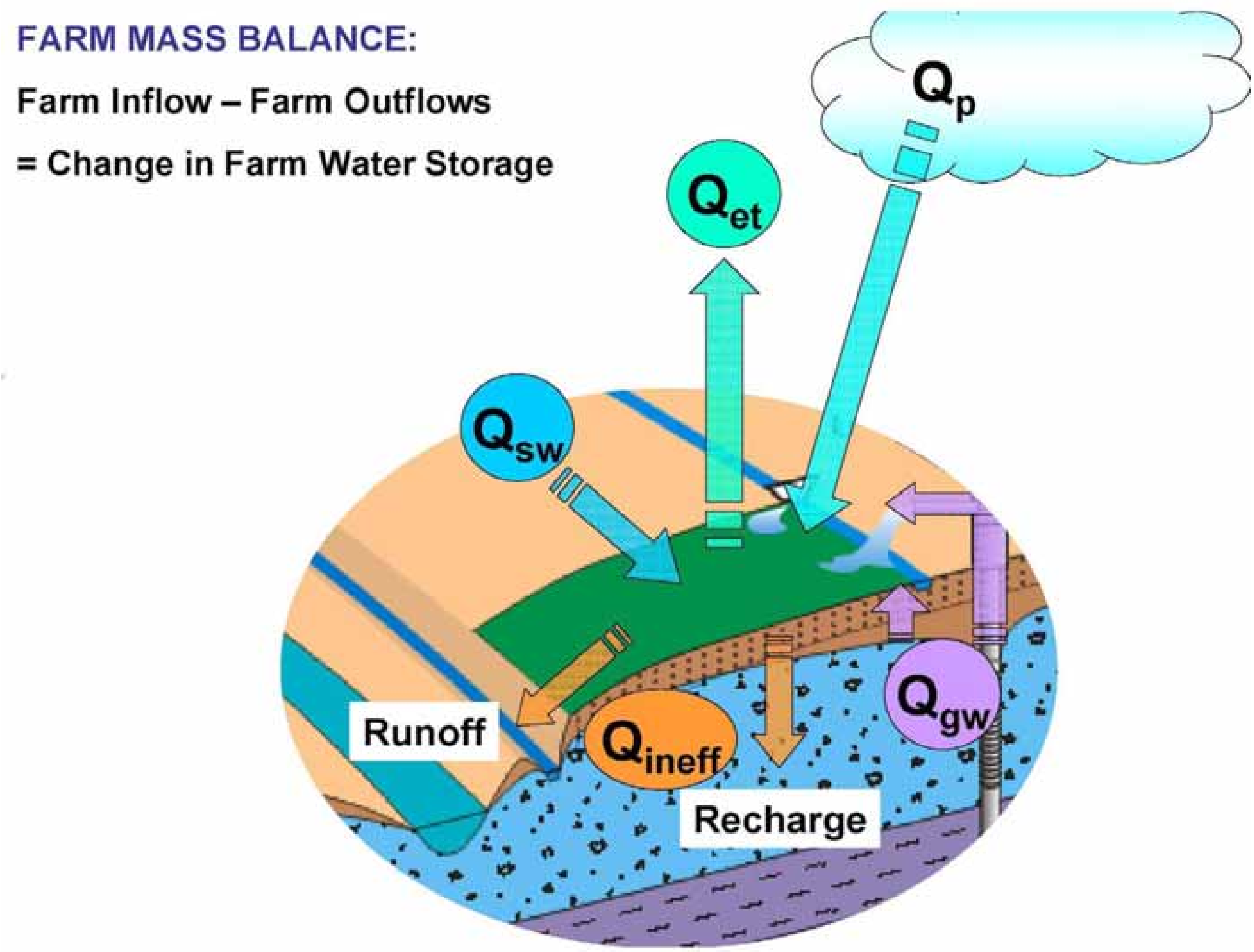

Fig. 4. Components of the mass balance in the FARM Process

The basic FARM Process input includes values that can be determined, such as

- Land use, including crop types
- Water deliveries, ranging from non-routed (e.g. delivered through pipelines) to fully routed (e.g. diversion from simulated streams or canals)
- Precipitation
- Reference ET and crop coefficients for calculating potential ET
- Soil types
- Root depths
- Well locations & construction

The primary output is

- Recharge from excess precipitation and irrigation
- Ground-water pumping required to meet crop demand, which is automatically implemented using wells
- Ground-water uptake by crops underlain by a shallow water table

Most importantly, the FARM Process allows realistic simulation of irrigated agriculture within MODFLOW by including the key processes involved.

Proposed enhancements to the FARM Process, pending funding, are to:

1. Simulate changing solute concentration in the root zone by tracking loads from combined sources of irrigation, precipitation, and interaction with ground water; and
2. Salinity-dependent infiltration and transpiratory uptake

The Salinity Policy Group will need to develop an understanding of the historical effect of agricultural practices on salinity. The FARM Process is an excellent tool for simulating the hydrologic effects of agriculture, and with the proposed enhancements would be ideal for simulating the evolution of salinity in the agriculturally dominated Central Valley. Because this link to transport is fundamental, this tool that can be used for assessing salinity management options could also be used to simulate the movement of other constituents such as nitrates, pathogens, natural contaminants (e.g. metals), or other anthropogenic compounds.

These enhancements will allow the direct simulation of long-term effects of various historical and future agricultural practices on the salinity of the root zone and underlying ground water.

Local Grid Refinement (LGR) Package

The LGR Package was designed to support (1) simultaneous execution of coarse-gridded "parent" models and embedded fine-gridded "child" models, and (2) linkage between models of different types (e.g. finite element and finite difference). Ongoing improvements will soon allow seamless tracking of particles through parent and child models.

This tool greatly improves our ability to scope in to small areas within a large model domain and explore local-scale processes in detail while still maintaining a connection to the inflows and outflows of the regional flow system.

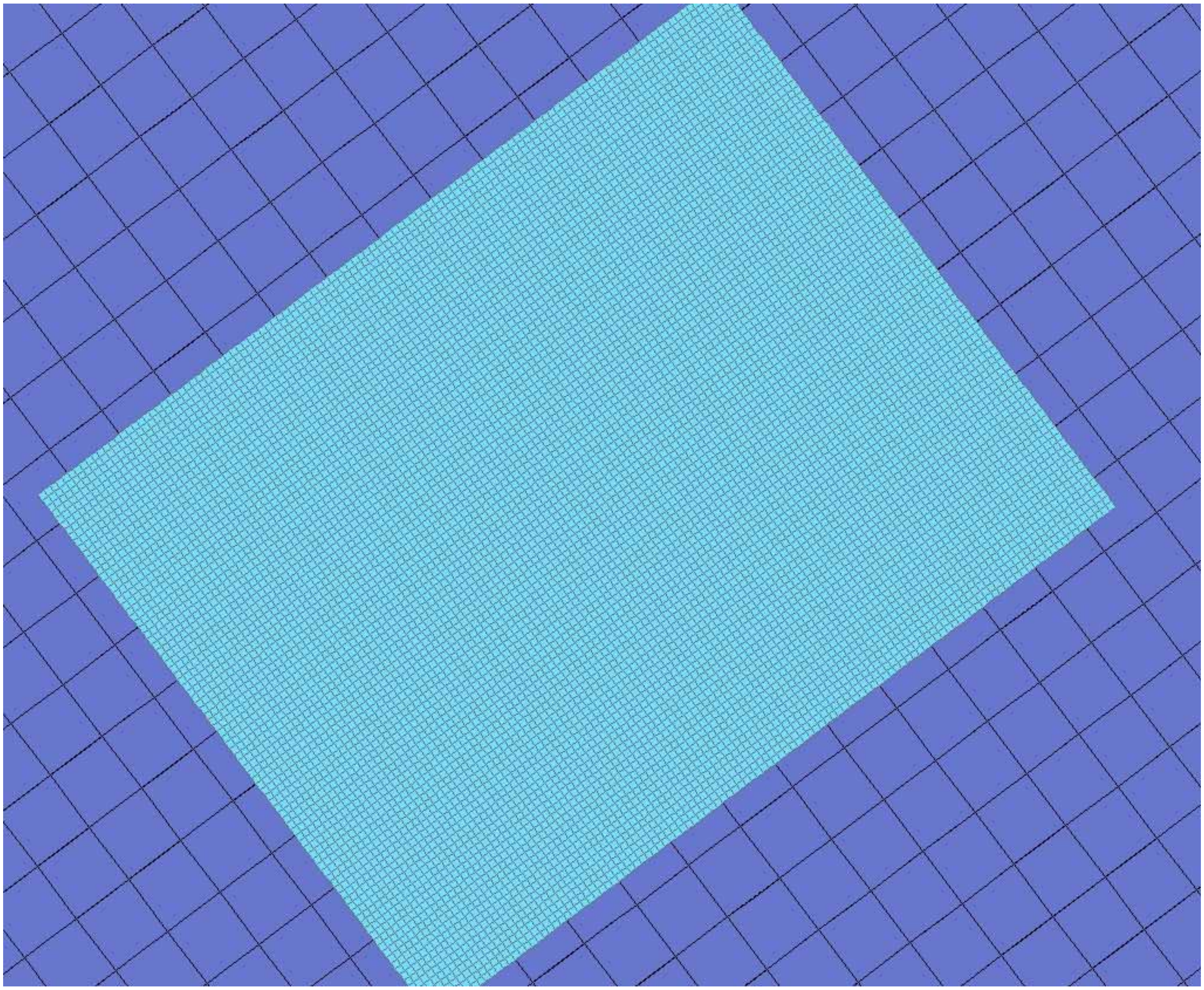

Fig. 5. *Local-scale model nested within a regional-scale model using the Local Grid Refinement (LGR) capability of MODFLOW*

While using models to develop an understanding of the distribution of salinity and to evaluate salinity management alternatives, the Salinity Policy Group will likely need to focus on various geographic areas at different scales, driven by data availability and local hydrology. LGR provides the flexibility to do so, as well as the ability to link separate models of incompatible type. This linkage currently works with MODFLOW, and the capability to link with other models, including finite-element models, is being developed by the USGS.

Solute Transport

Solute transport with the Ground-water Transport Process (GWT) is now included in the MODFLOW suite, allowing rapid implementation once a flow model is in place. Recent advances in MODFLOW solute transport capabilities include simulated transport through rivers, lakes, and multi-aquifer wells. As always, one can also use MODFLOW flux output as input to other solute transport codes, many of which are designed to read MODFLOW output.

Management optimization tools

MODFLOW now contains optimization software, the Ground-Water Management (GWM) package, for rapidly calculating the optimal solution to a posed problem given specified decision variables (things managers can control) and constraints (specified limits).

The GWM package, and many other types of optimization software that the USGS has extensive experience with, can be invaluable for rapidly and quantitatively exploring a wide range of management alternatives. The alternative is to try to find (with no guarantee of success) the optimal solution through trial and error, which is time intensive, particularly if model execution times are long.

It is likely that the Salinity Policy Group will consider several management alternatives at multiple locations, because the Central Valley hydrology is highly variable – what works best in one area may not in the next. Optimization tools would be a valuable resource in this case, resulting in time and money saved, and highly quantitative comparisons of the alternatives.

The FARM Process, described above, also has management optimization capabilities built in that allow the simulation of drought scenarios with the possibility of assessing acreage optimization, water stacking onto priority crops, or deficit irrigation. With the proposed linkage to salinity transport, these tools for assessing drought scenarios can additionally simulate the potential reduced crop yields from increased salinity.

Recently developed multi-scale USGS models in the Central Valley

Local-scale models

Local-scale models were recently developed for the Modesto area, and a location along the Merced River.

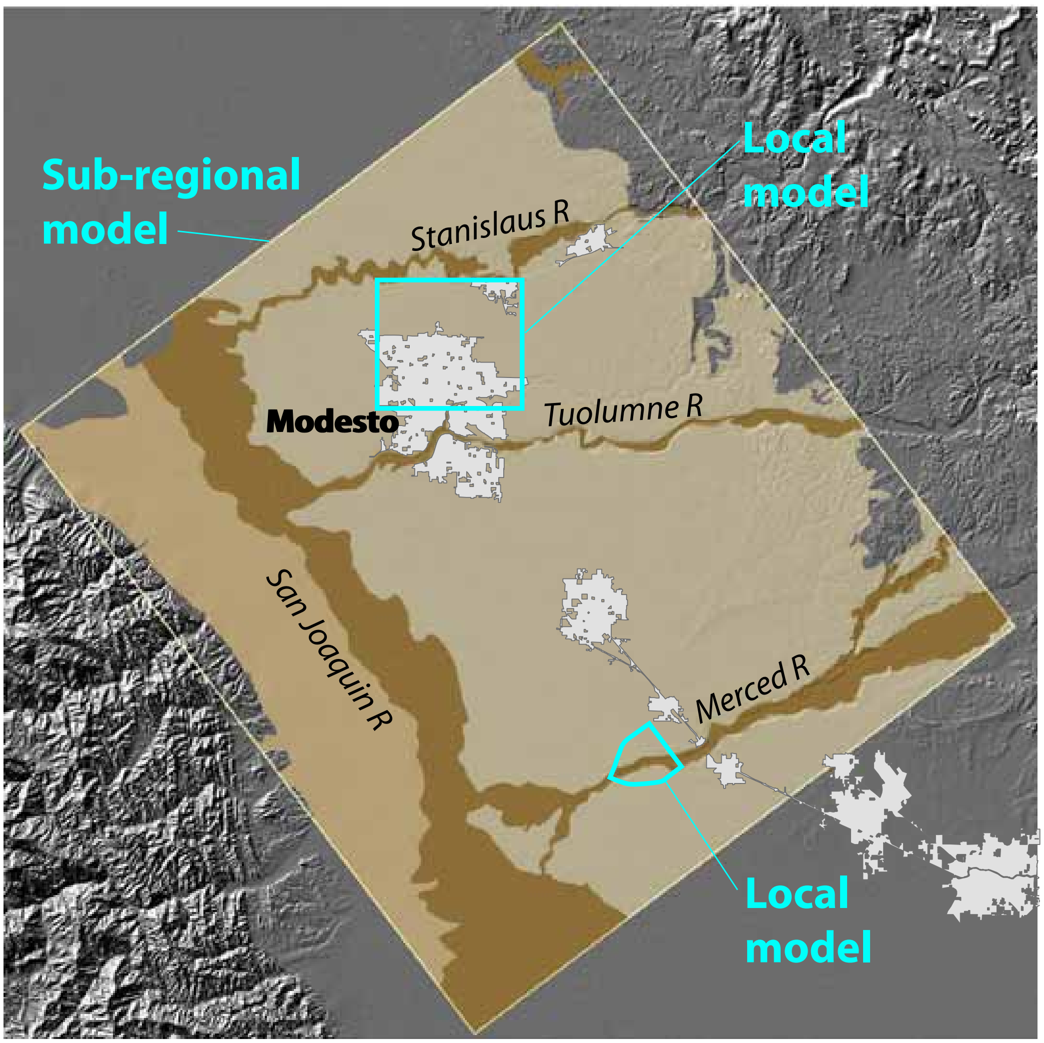

Fig. 6.
Two local-scale models nested within a sub-regional model of the Modesto-Turlock area

These local models are steady-state, represent modern conditions (water year 2000), and were developed for the purpose of simulating solute transport. Both models have finely-spaced grids in all dimensions and incorporate the heterogeneity of aquifer materials, as described above. They represent very different land uses and hydrologic regimes:

Modesto area

- Urban area rapidly expanding into agricultural areas
- Agriculture influences quality of urban water supply, but also provides local recharge
- Urban ground-water pumping is concentrated and deep, driving downward migration of agricultural and urban contaminants

Merced River area

- Agricultural and native riparian land use
- Ground-water pumping minimal; canal water used for irrigation
- Primary ground-water discharge is to the Merced River

Sub-regional-scale models

Two sub-regional-scale models were recently developed, one on the east side of the San Joaquin Valley in the Modesto area (shown above with the embedded local-scale models), and one on the west side that includes the Grasslands Drainage Area and the northern third of Westlands Water District (shown below).

Both models are finely gridded for their scale, with cells ¼-mile on a side and 10-16 layers. Each includes an explicit representation of sediment texture, as described above, and detailed water budgets.

The published Modesto-area model is steady-state, representing modern conditions (water year 2000). A transient version (1960-2004, monthly) is being developed, and will be completed in 2008. The transient version uses the FARM process to simulate irrigated agriculture in 43 subareas. Subsequent work will involve linking optimization tools to the model for exploration of management alternatives for addressing local ground-water issues.

The sub-regional model of the Modesto area would be a robust tool for developing an understanding of the salinity distribution on the east side, and for evaluating salinity management options appropriate for east-side conditions. The FARM Process is used in the 1960-2004 version, which represents the potential for simulating salt concentrations in the root zone.

Fig. 7.
A sub-regional model of the Grasslands Drainage Area and northern Westlands Water District

The Grasslands-area model is transient (1973-2000) and simulates water levels and drain flow on a monthly basis. A comprehensive map of tile drain locations was developed as part of this work, and is represented in the model.

The sub-regional model of the Grasslands area would be an excellent tool for developing an understanding of the salinity distribution on the west side. Its predecessor, developed by the USGS 20 years ago, has been used extensively by consultants, academics, and the USGS for evaluating salinity management options on the west side of San Joaquin Valley. This updated version improves our simulation of drain flow and is spatially and temporally refined, making it a powerful tool with a strong history.

A regional-scale model

An extensive update of the original USGS Central Valley Regional Aquifer Systems Analysis (CVRASA) is nearing completion. This new model, CVRASA2, includes the entire Central Valley aquifer system and covers the period from 1961-2003 on a monthly basis.

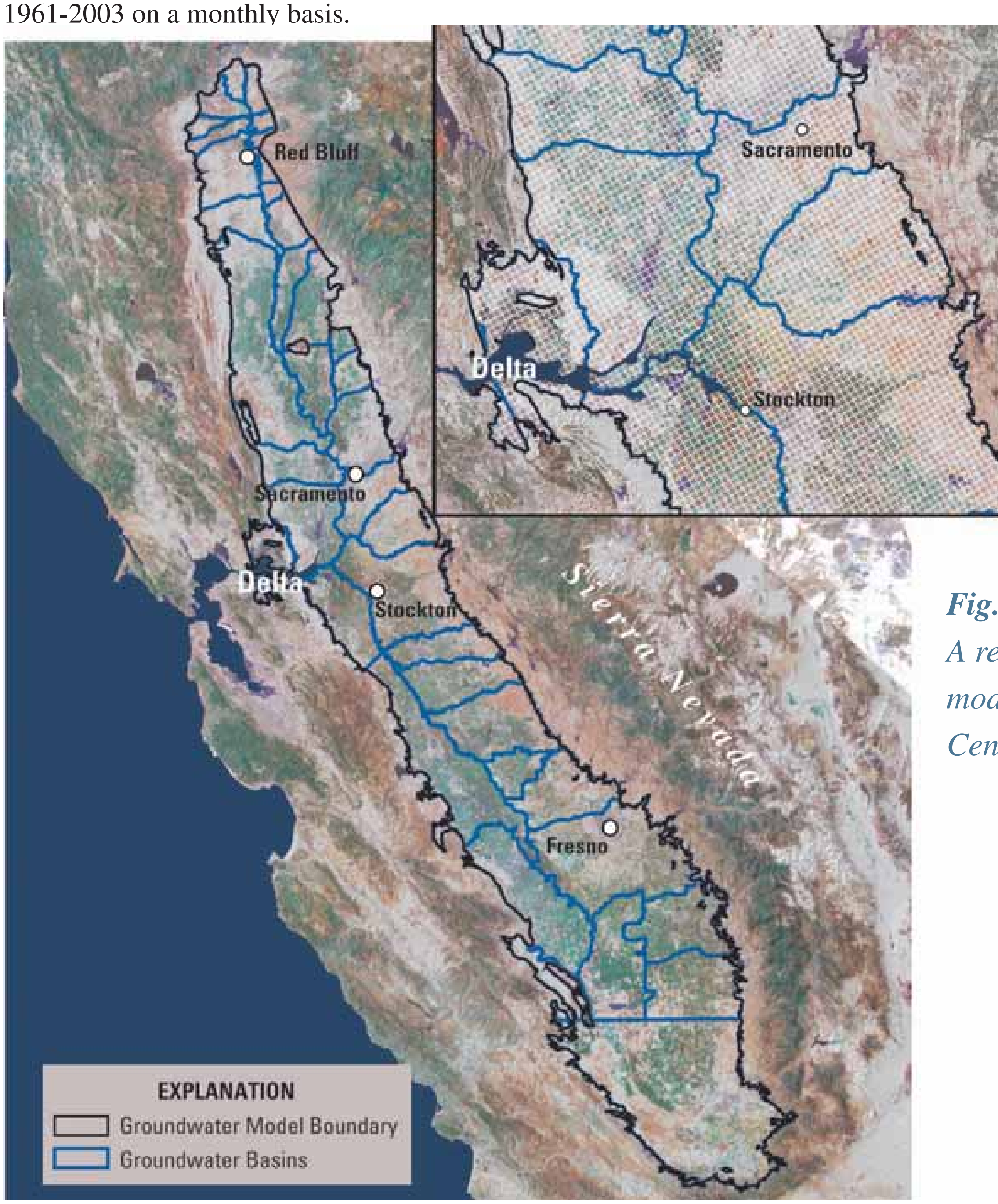

Fig. 8.
A regional-scale model of the Central Valley

CVRASA2 is finely gridded at 1 square mile and 10 layers. As with all of the other recent models described herein, sediment texture (from about 8,500 drillers' logs) and other information was used to develop a geologic model, which in turn was used to estimate hydraulic conductivity for every cell in the model.

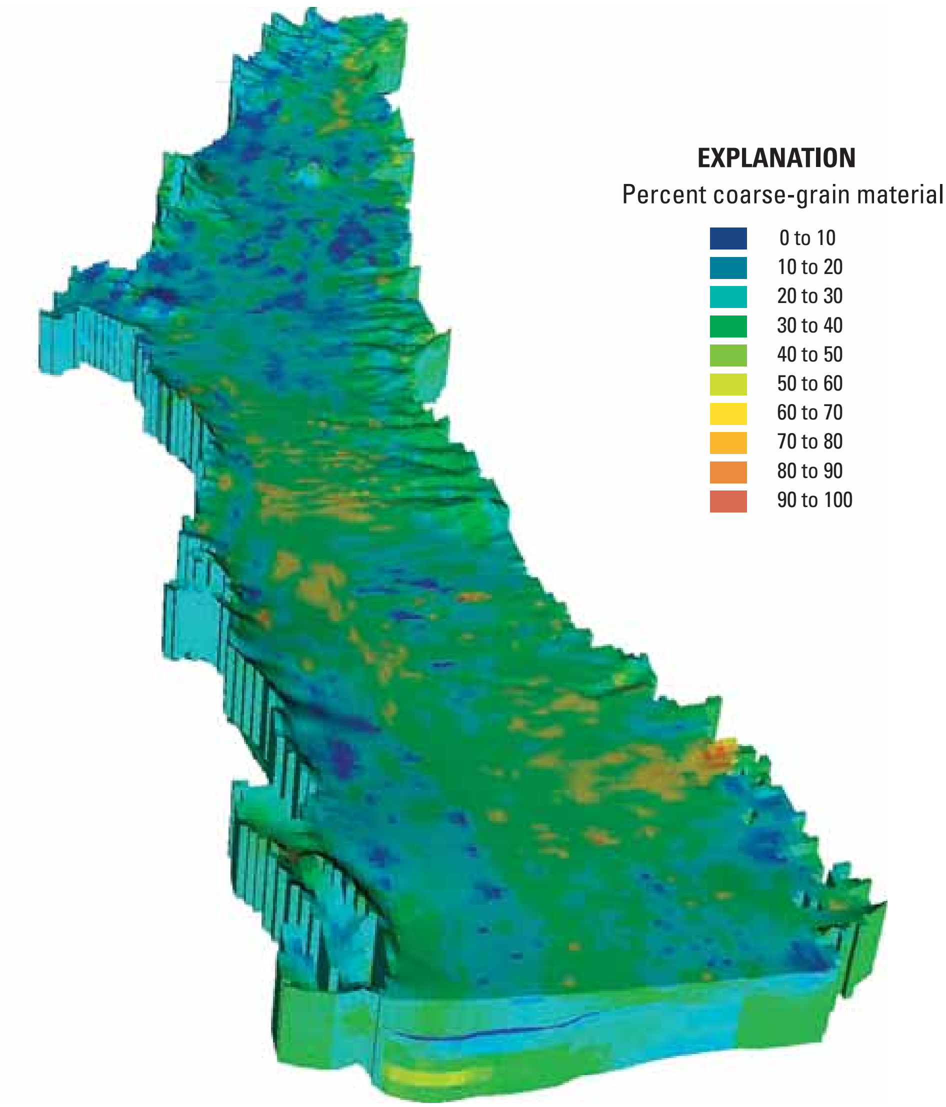

Fig. 9.
Sediment texture in the Central Valley

The FARM process was used to simulate irrigated agriculture, including routed diversions from rivers. Land subsidence, an important side-effect of overdraft in (primarily) the San Joaquin Valley, is simulated in CVRASA2. Intra-borehole flow, an important mechanism for vertical flow and solute transport in parts of the valley, is simulated across the Corcoran Clay.

CVRASA2 is designed to support the study of valley-wide processes, such as salinity transport, and to provide reasonable boundary conditions for finer-gridded models of smaller areas within the Central Valley. Therefore, it should prove to be a very useful tool for the Salinity Policy Group in helping to understand the current salinity distribution at the regional and local scales, and for extending regionally the analysis of potential salinity management actions.

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